Muon FFAG Design Updates

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Stages in FFAGs

- Different numbers of stages to get from 2.5 to 20 GeV
- 2 stages significantly more expensive than 3
  - Result: significantly worse
  - More cells, larger apertures, fewer turns
  - But fields and magnet lengths lower
- 3 stages wins slightly over 4
  - Machine cost slightly lower for 4, but decays make 4 stages worse
  - Extra cost of transfer line also adds to 4 stage cost
  - Prefer fewer stages to more
- Cost per GeV at low energy stays pretty flat
  - For 2.5 GeV to something ring: 2.1 GeV cost me 30.1 PB/GeV
  - For something to 20 GeV ring: 2.9 GeV cost me 18.3 PB/GeV
  - Almost certainly better to give low energy a SMALLER range

Stages in FFAGs: Table

Min. total energy (GeV)	2.5	4.2	7.1	11.9	2.5	5.0	10.0	2.5	7.1
Max. total energy (GeV)	4.2	7.1	11.9	20.0	5.0	10.0	20.0	7.1	20.0
Number of cells	34	38	46	57	50	63	82	101	152
Number of cavities	26	30	35	38	42	48	56	88	97
RF voltage (MV)	331	382	434	477	534	606	704	1114	1230
Turns	5.2	7.6	11.4	17.7	4.7	8.5	15.0	4.2	11.3
Circumference (m)	144	174	228	306	204	279	400	389	653
Decay (%)	3.6	3.8	4.4	5.4	4.2	5.1	6.5	5.8	9.1
Machine cost (PB)	53.0	56.7	61.5	68.1	74.8	78.9	88.9	138.1	142.0
... per GeV (PB/GeV)	31.1	19.8	12.8	8.4	29.9	15.8	8.9	30.2	11.0
Marginal decay cost (PB)	18.0	18.9	21.9	27.1	21.1	25.6	32.3	28.9	45.5
Total machine cost (PB)	239.3				242.7			280.1	
Total decay cost (PB)	85.9				78.9			74.5	

Variable Frequency FFAGs

- Time of flight in FFAGs depends on energy
- If RF frequency doesn't change, this will cause you to get off the RF crest if you accelerate too slowly
- However, if the RF frequency is variable, you can stay on-crest, using as little voltage as you want
- With muons, we have decays: want a high average gradient
- Find cost-minimum lattices with decays where no attempt is made at controlling time of flight
- Compare to cost-minimum lattices with control on time of flight

Variable Frequency FFAGs: Table

Minimum total energy (GeV)	2.5	5	10	2.5	5	10
Maximum total energy (GeV)	5	10	20	5	10	20
$V/(\omega \Delta T \Delta E)$	1/6	1/8	1/12	—	—	—
No. of cells	50	65	82	38	47	65
No. of cavities	58	49	56	30	36	45
RF voltage (MV)	534	620	704	380	464	566
Turns	4.7	8.2	15.0	6.6	10.8	17.7
Circumference (m)	204	286	400	169	232	350
Decay (%)	4.2	5.1	6.5	4.8	5.4	6.6
Magnet cost (PB)	39.4	37.2	39.1	40.0	40.6	42.7
RF cost (PB)	30.3	35.2	39.9	21.5	26.3	32.1
Linear cost (PB)	5.1	7.2	10.0	4.2	5.8	8.8
Machine cost (PB)	74.8	79.5	88.9	65.7	72.8	83.6
Extra decay cost (PB)	—	—	—	3.1	1.5	1.0
Cost reduction (%)	—	—	—	8.0	6.6	4.9
$\Delta f/f$ (10^{-3})	—	—	—	5.4	2.8	1.3
Variation time (μs)	—	—	—	2	5	12

Analysis

- The cost reductions are relatively modest
  - Cell lengths go up, so RF efficiency goes down: more decays
  - Machine gets shorter, magnet costs go up (aperture increase)
  - Less RF required, this plus linear cost gives reduction
- For all three stages, cost increase is 20% of final RF cost
  - Making the RF frequency variable will cost something!
  - RF cost includes cavity itself plus power, cryostat, etc.
  - Thus, may be larger percentage of cavity cost.
  - Power, cryo costs may also increase!
- Probably not worth the trouble to make RF variable
  - Cost reduction is relatively modest
  - High technical risk
- Greater cost reduction at low energy
  - But frequency variation harder there